APPARATUS AND METHOD OF FORMING CHANNELS IN A HEAT-EXCHANGING DEVICE

Related Application

This application claims priority under 35 U.S.C. § 119(e) of the co-pending U.S. provisional patent application Serial Number 60/455,729, filed on March 17, 2003, and titled "Microchannel Heat Exchanger Apparatus with Porous Configuration and Method of Manufacturing Thereof." The provisional patent application Serial Number 60/455,729, filed on March 17, 2003, and titled "Microchannel Heat Exchanger Apparatus with Porous Configuration and Method of Manufacturing Thereof" is hereby incorporated by reference.

Field of the Invention

This invention relates to the field of heat exchangers. More particularly, this invention relates to a method and apparatus for circulating a cooling material through optimally shaped channels and other geometric structures in a heat exchanger.

Background of the Invention

Certain heat sinks use pumps to pump a cooling material through a portion of the heat sink overlying a heat-generating source. The cooling material absorbs the heat generated by the heat-generating source and carries it away from the heat-generating source, thereby cooling the heat-generating source. Pumps used to transmit the cooling material through the heat sink are operated at maximum flow rates.

Cooling materials transmitted along channels used in these heat sinks generally suffer from excessive and non-uniform pressure drops. The pumps used to circulate cooling materials, already overworked to pump the cooling material at high rates, require even more energy to account for these pressure drops.

Heat sinks made according to U.S. patent application Serial Number 10/612,241, titled "Multi-Level Microchannel Heat Exchangers," Attorney Docket No. COOL-01400, filed July 1, 2003, require numerous semiconductor processing and assembly steps. While providing enhanced cooling capacity, these processing steps likely increase the cost of the heat exchanger. The benefits afforded by these processing and assembly steps may not be warranted by the added costs of manufacturing.

Accordingly, what is needed is a structure and a method of efficiently manufacturing a heat exchanger that provides for uniform pressure flows for the transmission of a cooling material.

Brief Summary of the Invention

A heat exchanger circulates a cooling material that absorbs heat from a heat-generating source and carries the heat away from the heat-generating source, thereby cooling the heat-generating source. The heat exchanger can thus be used to cool a variety of heat sources, such as semiconductor devices, batteries, motors, walls of process chambers, and any source that generates heat.

In a first aspect of the present invention, a method of forming a heat exchanger comprises forming a manifold layer defining a plurality of apertures and forming an interface layer comprising one or more narrowing trenches. Each aperture is positioned on one side of a narrowing trench, whereby a path is defined from a first aperture, through a narrowing trench, and to a second aperture. In a first embodiment, the interface layer comprises a material exhibiting properties of anisotropic etching. Preferably, the material comprises a <110> oriented silicon substrate. In another embodiment, forming an interface layer comprises etching the <110> oriented silicon substrate in an etchant to produce a <111> oriented surface defining a sloping wall of a narrowing trench. Alternatively, the material is any orientation of silicon and is etched in an anisotropic plasma etch to form one or more narrowing trenches. In further

embodiments, the etchant comprises potassium hydroxide (KOH) or tetramethyl ammonium hydroxide (TMAH). In another embodiment the one or more narrowing trenches are formed by a machining process such as milling, sawing, drilling, stamping, electrical discharge machining (EDM), wire EDM, coining, die casting, investment casting, or any combination of these. Alternatively, the one or more narrowing trenches are formed by electroplating, metal injection molding, LIGA processes, casting, or any combination of these.

In another embodiment, the manifold layer and the interface layer are formed of a monolithic device. In another embodiment, the method further comprises coupling the manifold layer to the interface layer. Coupling the manifold layer to the interface layer can comprise adhesively bonding the manifold layer to the interface layer, thermally fusing the manifold layer to the interface layer, anodically bonding the manifold layer to the interface layer, and eutectically bonding the manifold layer to the interface layer. In another embodiment, the manifold layer comprises a material selected from the group consisting essentially of a plastic, a glass, a metal, and a semiconductor.

In another embodiment, forming the manifold layer comprises forming a first plurality of interconnected hollow fingers and a second plurality of interconnected hollow fingers. The first plurality of interconnected hollow fingers provides flow paths to the one or more first apertures and the second plurality of interconnected hollow fingers provides flow paths from the one or more second apertures. Preferably, the first plurality of interconnected hollow fingers and the second plurality of interconnected hollow fingers lie substantially in a single plane.

In another embodiment, the method further comprises coupling a pump to the first plurality of interconnected hollow fingers. In another embodiment, the method further comprises coupling a heat-generating source to the interface layer. In another embodiment, the method comprises integrally forming a bottom surface of the interface layer with the heat-generating source. In another embodiment, the heat-generating source comprises a semiconductor microprocessor. In another embodiment, the method further comprises introducing a cooling material to the pump, so that the pump circulates the cooling material along the first plurality of

fingers, to the one or more first apertures, along a the plurality of narrowing trenches, to the one or more second apertures, and to the second plurality of fingers, thereby cooling the heat-generating source. In another embodiment, the cooling material comprises a liquid, such as water. In other embodiments, the cooling material comprises a liquid/vapor mixture. In another embodiment, each aperture lies substantially in a single plane, parallel to a lower surface of the interface layer. In another embodiment, the manifold layer comprises a surface that extends into each narrowing trench and substantially conforms to a contour of each narrowing trench. In another embodiment, a narrowing trench has a depth:width aspect ratio of at least approximately 10:1.

In another embodiment, the method further comprises coupling an intermediate layer between the manifold layer and the interface layer. The intermediate layer comprises a plurality of openings positioned over the plurality of apertures, thereby controlling the flow of a cooling material to the paths.

In a second aspect of the present invention, a heat exchanger comprises a manifold layer defining a plurality of apertures, and an interface layer comprising a plurality of narrowing trenches. Each aperture is positioned on one side of a narrowing trench, whereby a path is defined from a first aperture, through a narrowing trench, and to a second aperture. In another embodiment, the interface layer comprises a material exhibiting anisotropic etching. Preferably, the material comprises a <110> oriented silicon substrate. In another embodiment, the interface layer is formed by etching the <110> oriented silicon substrate in an etchant to produce a <111> oriented surface defining a sloping wall of a narrowing trench. In other embodiments, the etchant comprises potassium hydroxide (KOH) or tetramethyl ammonium hydroxide (TMAH). In one embodiment, the narrowing trenches are formed by a machining process, such as milling, sawing, drilling, stamping, EDM, wire EDM, coining, die casting, investment casting, or any combination of these. Alternatively, the narrowing trenches are formed by electroplating, metal injection molding, LIGA processes, casting, or any combination of these.

In another embodiment, the manifold layer and the interface layer are formed of a

monolithic device. In another embodiment, the manifold layer is coupled to the interface layer. The manifold layer can be coupled to the interface layer by adhesive bonding, thermal fusing, anodic bonding, or eutectic bonding. In another embodiment, the manifold layer comprises a material selected from the group consisting essentially of a plastic, a glass, a metal, and a semiconductor.

In another embodiment, the manifold layer comprises a first plurality of interconnected hollow fingers and a second plurality of interconnected hollow fingers. The first plurality of interconnected hollow fingers provide flow paths to the one or more first apertures and the second plurality of interconnected hollow fingers providing flow paths from the one or more second apertures. Preferably, the first plurality of interconnected hollow fingers and the second plurality of interconnected hollow fingers lie substantially in a single plane.

In another embodiment, the manifold layer comprises a first layer comprising one or more of the first apertures and one or more of the second apertures, and a second layer comprising a first plurality of interconnected fingers and a second plurality of interconnected fingers. The first plurality of interconnected fingers provides flow paths to the one or more first apertures and the second plurality of fingers provides flow paths from the one or more second apertures.

In another embodiment, the heat exchanger further comprises a pump coupled to the first plurality of fingers. In another embodiment, the heat exchanger further comprises a heat-generating source coupled to the interface layer. In another embodiment, the heat-generating source comprises a semiconductor microprocessor. In another embodiment, the heat-generating source is integrally formed to a bottom surface of the interface layer. In another embodiment, each aperture lies substantially in a single plane, parallel to a lower surface of the interface layer. In another embodiment, the manifold layer comprises a surface that extends into each trench and substantially conforms to a contour of each narrowing trench. In another embodiment, a depth:width aspect ratio for at least one of the plurality of narrowing trenches is at least 10:1.

In another embodiment, the heat exchanger further comprises an intermediate layer positioned between the manifold layer and the interface layer. The intermediate layer comprises

a plurality of openings positioned over the plurality of apertures, thereby controlling the flow of a cooling material to the paths.

Brief Description of the Several Views of the Drawings

Figure 1A is a side cross-sectional view of an interface layer and a portion of a manifold layer, together forming a heat exchanger in accordance with the present invention, coupled to a heat-generating source.

Figure 1B is a side cross-sectional view of the heat exchanger and heat-generating source of Figure 1A, showing flow paths traveled by a cooling material.

Figure 2 is a side cross-sectional view of an interface layer and a portion of a manifold layer, together forming a heat exchanger in accordance with the present invention, coupled to a heat-generating source, with the manifold layer having a curving bottom surface that extends into a plurality of the trenches that forms the interface layer.

Figure 3 is a side cross-sectional view of an interface layer and a portion of a manifold layer, together forming a heat exchanger in accordance with the present invention, coupled to a heat-generating source, with the manifold layer having a piecewise curving bottom surface that extends into a plurality of the trenches that form the interface layer.

Figure 4 is a perspective view of the manifold layer and the interface layer of Figure 1A.

Figure 5 is a perspective view of the manifold layer of Figure 4.

Figure 6A is a top cross-sectional view of the manifold layer and the interface layer of Figure 4, showing how the narrowing trenches of the interface layer align with the fingers and the solid portions of the manifold layer.

Figure 6B is a top cross-sectional view of the manifold layer and the interface layer of Figure 6A, showing flow paths for a cooling material.

Figure 7 is a perspective view of the manifold layer and the interface layer of Figure 6B, again showing a flow path.

Figure 8 is a perspective view of the manifold layer of Figure 4, an intermediate layer,

and the interface layer of Figure 4, together forming a heat exchanger in accordance with the present invention.

Figure 9 is a side cross-sectional view of the heat exchanger of Figure 8, showing several flow paths.

Figure 10 is a perspective view of a manifold layer of Figure 4, an intermediate layer, and the interface layer of Figure 4, together forming a heat exchanger in accordance with the present invention.

Figure 11 is a side cross-sectional view of the heat exchanger of Figure 10, showing a flow path.

Figure 12A is a top view of an interface layer in accordance with one embodiment of the present invention.

Figure 12B is side cross-sectional view of the interface layer of Figure 12A and a manifold layer aligned with the interface layer, in accordance with the present invention.

Figure 12C is more detailed top view of the interface layer of Figure 12A.

Figures 13A-D show the steps used to form an interface layer, in accordance with the present invention.

Detailed Description of the Invention

Figure 1 is a side cross-sectional view of a portion of a heat exchanger 110 coupled to a heat-generating source 180. The heat exchanger 110 comprises a manifold layer 101 and an interface layer 105. The manifold layer 101 comprises a surface having a plurality of apertures 101A-E and a plurality of solid portions 101J-M. The interface layer 105 comprises a plurality of narrowing trenches 105A-D and is coupled at a bottom surface to the heat-generating source 180. Each narrowing trench is defined by a sloping sidewall, a substantially planar floor, and a second sloping sidewall. Each trench is narrowing in that a cross-sectional area at an upper plane of a trench is larger than a cross-sectional area at a bottom plane of the trench, realized, for example,

by sloping sidewalls. As described in more detail below, the plurality of apertures 101A-E, the plurality of solid portions 101J-M, and the narrowing trenches 105A-D define flow paths or channels that can accommodate the flow of a cooling material. The cooling material comprises a fluid, such as a liquid, a vapor, air, or any combination of these. Circulating the cooling material in a narrowing trench above the heat-generating source 180 will cool that heat-generating source at an area below the narrowing trench.

Figure 1B is the side cross-sectional view of the heat exchanger 110 and heat-generating source 180 depicted in Figure 1A. Figure 1B further illustrates a cooling material introduced into the apertures 101B and 101D and removed from the apertures 101A, 101C, and 101E. Arrows in Figure 1B indicate the direction of flow for the cooling material. The squiggly arrows show the path of heat from the heat-generating source 180 to the cooling material. Thus, as illustrated in Figure 1B, in operation a cooling material is introduced into the apertures 101B and 101D by, for example, a pump (not shown) coupled to the apertures 101B and 101D. The cooling material introduced into the aperture 101B on the flow path 120 is divided into the flow paths 121 and 122. That portion of the cooling material traveling along the flow path 121 is channeled from the aperture 101B, to the narrowing trench 105A, and to the aperture 101A. The cooling material traveling along the flow path 121 absorbs the heat conducted by the interface layer 105 from the heat-generating source 180 to the cooling material substantially adjacent to the narrowing trench 105A. The cooling material traveling along the flow path 121 is then channeled to the aperture 101A, carrying the absorbed heat away from the heat-generating source 180, and thus cooling the heat-generating source 180 at a position substantially adjacent to the narrowing trench 105A. That portion of the cooling material traveling along the flow path 122 is channeled from the aperture 101B, to the narrowing trench 105B, and to the aperture 101C, thus cooling the heat-generating source 180 at a location substantially adjacent to the narrowing trench 105B. As illustrated in Figure 1B, the cooling material traveling along the flow path 122 combines with the cooling material traveling along a flow path 131 to form cooling material traveling out of the aperture 101C along a flow path 130.

Similarly, cooling material introduced into the aperture 101D along a flow path 135 is divided into flow paths 131 and 132. That portion of the cooling material traveling along the flow path 131 is channeled from the aperture 101D, to the narrowing trench 105C, and to the aperture 101C, thus cooling the heat-generating source 180 at a location substantially adjacent to the narrowing trench 105C. As discussed above, the cooling material from the flow path 131 is combined with the cooling material from the flow path 122 to form cooling material on a flow path 130 at the aperture 101C. That portion of the cooling material traveling along the flow path 132 is channeled from the aperture 101D, to the narrowing trench 105D, and to the aperture 101E, thus cooling the heat-generating source 180 at a location substantially adjacent to the narrowing trench 105D.

The cooling material removed from the apertures 101A, 101C, and 101E can be processed in many ways. For example, the cooling material can removed from the heat exchanger 110, or it can be re-cooled and reintroduced into the apertures 101B and 101D.

As described in more detail below, the manifold layer 101 can have many shapes useful for providing a cooling material to the apertures 101B and 101D and for removing the cooling material from the apertures 101A, 101C, and 101E. It will be appreciated that the roles of the apertures can be reversed or assigned in different combinations. For example, the apertures 101A, 101C, and 101E can be used to introduce a cooling material into the channels formed by the narrowing trenches and the apertures 101B and 101D used to remove the cooling material from the channels formed by the narrowing trenches. Also, while the drawings show only five apertures 101A-E and four narrowing trenches 105A-D, fewer or more apertures and narrowing trenches can be formed in accordance with the present invention.

Preferably, the interface layer 105 has a thermal conductivity sufficient to conduct heat generated at the heat-generating source 180 to the cooling material traveling along the fluid paths 121, 122, 131, and 132. Preferably, the interface layer 105 has a thermal conductivity of approximately 20 W/m-K or larger. Preferably, the interface layer comprises a silicon material. It will be appreciated, however, that the interface layer 105 can comprise other materials, such as

a metal, and can have a thermal conductivity smaller than 20W/m-K.

It is believed that fluid paths channeled along sloping sidewalls, rounded corners, and other non-perpendicular edges in accordance with the present invention have advantages over channels having substantially perpendicular edges. Because sloping sidewalls provide a more uniform flow path than do right-angled sidewalls, there are fewer pressure drops along the flow path. Thus, a pump requires less energy to transmit the cooling material along the channels and thus forms part of a more efficient heat-exchanging system.

Figure 2 is a side cross-sectional view of a heat exchanger 210, in accordance with the present invention, coupled to a heat-generating source 280. The heat-exchanger 210 comprises the interface layer 105 of Figure 1A and a manifold layer 201 comprising a plurality of apertures 201A-E and a plurality of solid portions 201J-M. Figure 2 also depicts a flow path 220 from the aperture 201B, divided into a flow path 221 to the aperture 201A and a flow path 222 to the aperture 201C. A flow path 235 from the aperture 201D is divided into the flow paths 231 and 232. The flow path 231 is combined with the flow path 222 to form a flow path 230 at the aperture 201C. The flow path 232 extends to the aperture 201E. As illustrated in Figure 2, a bottom surface of the solid portion 201J that forms part of the flow path 221 extends into the narrowing trench 205A and substantially conforms to the contour of the narrowing trench 205A. The bottom surface of the solid portion 201J thus has a non-perpendicular and preferably rounded surface that forms part of the flow path 221. This configuration is expected to enhance the fluid flow of the cooling material at the bottom of each narrowing trench 105A, 105B, 105C, and 105D, thereby enhancing the heat removal while reducing the pressure drops. A bottom surface of the solid portions 201K-M, forming part of the flow paths 222, 231, and 232, respectively, have similar contours.

It will be appreciated that the bottom surfaces of the solid portions 201J-M, which form part of the flow paths for the heat exchanger 210 and substantially conform to the contour of the narrowing trenches 105A-D, can have other shapes, such as a polygonal shape that approximately mirrors the shape of the narrowing trenches 105A-D. For example, Figure 3 illustrates a cross-

sectional diagram of a heat exchanger 250, in accordance with the present invention, coupled to the heat-generating source 280. The heat exchanger 250 comprises the interface layer 105 described above and a manifold layer 265 having apertures 265A-E and solid portions 265J-M. Figure 3 also shows an exemplary flow path 261 from the aperture 265B to the aperture 265A. The solid portions 265J-M each has a bottom surface that extends into each of the plurality of narrowing trenches 105A-D, respectively. The solid portion 265J is exemplary. As illustrated in Figure 3, the bottom surface of the solid portion 265J is formed from piecewise straight edges, such as exemplary piecewise straight edges 270A-C, which extend into the narrowing trench 105A. As described above, it will be appreciated that because the bottom surface of the solid portion 265J extends into the narrowing trench 105D, the flow path 261 has a smaller cross-sectional area than a corresponding flow path formed when the bottom surface of a solid portion does not extend into the narrowing channels. Thus, for example, the flow path 261 illustrated in Figure 3 has a smaller cross-sectional area than the flow path 121 illustrated in Figure 1B.

This structure has several advantages. For example, a cooling material traveling along the exemplary fluid flow paths 221 (Figure 2) and 261 (Figure 3) do not encounter any sharp edges as they travel between apertures, cooling a heat-generating source, and thus travel with fewer pressure drops. These structures also reduce the volume of the channel (flow path) along which the cooling material is transmitted. Forcing the same amount of cooling material along each smaller channel increases the velocity of the cooling material, which will increase the rate at which heat is carried away from the heat-generating source 280. Those skilled in the art will recognize other advantages with a manifold layer having a bottom surface that defines a portion of a channel, conforming to the shape of a narrowing trench.

It will be appreciated that while the above drawings depict symmetrical features, such as trenches and solid portions, heat exchangers in accordance with the present invention can have non-symmetrical features. Specifically, it may be advantageous to have larger openings at the outlets than at the inlets to accommodate the volume expansion associated with the transition from liquid to liquid/vapor mixtures. The narrowing trenches 105A-D (Figure 1A) can also have

different shapes and dimensions. And rather than aligned in symmetrical rows, the narrowing trenches can be apportioned in any number between rows, can even be staggered, or can be positioned and distributed in any manner to fit the application at hand. Furthermore, it will be appreciated that while Figures 1A-B, 2, and 3 all depict a one-dimensional view of a heat exchanger with four narrowing trenches 105A-D, it will be appreciated that a heat exchanger in accordance with the present invention can have fewer than or more than four trenches in a one-, two- or three-dimensional configuration.

Figure 4, for example, is a perspective view of a heat exchanger 300 with a plurality of narrowing trenches in a two-dimensional configuration, used to cool a heat-generating source (not shown). It is believed that using a large number of small narrowing trenches has advantages over using a small number of large narrowing trenches to cool a heat-generating source. It is believed that small narrowing trenches formed without any sharp angles advantageously reduce pressure drops associated with cooling materials transmitted through the heat exchanger, thus requiring less energy to pump the cooling material through the heat exchanger. It is also believed that the smaller narrowing trenches increase the surface-to-volume ratio of the cooling material to the surface of the heat-generating source, thus aiding in more efficiently cooling the heat-generating source.

The heat exchanger 300 comprises the manifold layer 101 and the interface layer 105, both of Figure 1A, but gives a more complete three-dimensional view of each. Figure 1A illustrates only a cross-sectional portion of the manifold layer 101. Figure 4 illustrates the manifold layer 101 with a portion of a top, enclosing surface 189 cut away to expose elements of the manifold layer 101, contained below the top surface 189 and described below. As described in more detail above, the interface layer 105 comprises the narrowing trenches 105A-D and narrowing trenches 106A-D and 107A-D. Because the narrowing trenches 106A-D and 107A-D perform similar functions to the narrowing trenches 105A-D, the following discussions will be limited to the narrowing trenches 105A-D. Figure 4 also shows a plane RR'SS' perpendicular to the top surface 189 and described below in relation to Figure 7.

Still referring to Figure 4, the manifold layer 101 comprises a first plurality of hollow fingers 196A-B (collectively, 196), a second plurality of hollow fingers 190A-C (collectively, 190), solid portions 101J-M, a first reservoir 195, a second reservoir 198, inlet ports 197A and 197B coupled to the first reservoir 195, and outlet ports 199A and 199B coupled to the second reservoir 198. Preferably, the hollow fingers 190 and 196 all lie substantially in a single plane, parallel to a bottom surface of the manifold layer 101. As described below, the hollow fingers 190 and 196 are openings in the manifold layer 101, providing communications path between a top surface of the manifold layer 101 and a bottom surface of the manifold layer 101. The hollow fingers 196 are coupled to the first reservoir 195 and thus to each other, and provide a flow (communication) path from the first reservoir 195 to a first portion of the bottom surface of the manifold layer 101. Thus, in operation, a cooling material can flow from the inlet ports 197A-B, to the first reservoir 195, to the hollow fingers 196, and through the bottom of the manifold layer 101 into the interface layer 105. Similarly, the hollow fingers 190 are coupled to the second reservoir 198 and thus to each other, and provide a flow path from the interface layer 105 up through the bottom of the manifold layer 101, and to the second reservoir 198. Thus, in operation, a cooling material can flow from the inlet ports 197A-B, through the hollow fingers 196, down to the interface layer 105, along a narrowing trench 105D, back up to the hollow fingers 190 in the manifold layer 101, and to the outlet ports 199A-B.

As illustrated in Figure 4, the hollow fingers 196 are interwoven with the hollow fingers 190 in that the hollow fingers 196 are interdigitated with the hollow fingers 190. Moreover, the solid portions 101J-M alternate with the hollow fingers 196 and the hollow fingers 190. Thus, the solid portion 101M is between the hollow fingers 190A and 196A, the solid portion 101L is between the hollow fingers 196A and 190B, the solid portion 101K is between the hollow fingers 190B and 196B, and the solid portion 101J is between the hollow fingers 196B and 190C. The solid portions 101J-M thus provide structure for the manifold layer 101. Figure 5 is a perspective view of the manifold layer 101 of Figure 4, with the top surface 189 (Figure 4) completely removed.

It will be appreciated that manifold layers used in accordance with the present invention can have configurations different from those described here. For example, the hollow fingers 190A-C need not be coupled to each other by the reservoir 198, and the hollow fingers 196A-B need not be coupled to each other by the reservoir 195. The plurality of hollow fingers 190 need not be interwoven with the plurality of hollow fingers 196. Manifold layers with any number and combination of hollow fingers can be used. Examples of manifold layers that can be used in accordance with the present invention are taught in co-pending U.S. patent application Serial Number 10/439,635, Attorney Docket No. COOL-00301, filed on May 16, 2003, and titled "Method and Apparatus for Flexible Fluid Delivery for Cooling Desired Hot Spots in a Heat Producing Device," which is hereby incorporated by reference.

Figure 6A is a top cross-sectional view of the manifold layer 101 aligned over the interface layer 105. When the manifold layer 101 is aligned over the interface layer 105, the two define a plurality of apertures 101A-E, as illustrated, for example, in Figure 1A. For example, as illustrated in Figures 6A and 1, the solid portion 101J overlies and spans a portion of the narrowing trench 105D, defining the apertures 101A and 101B; the solid portion 101K overlies and spans a portion of the narrowing trench 105B, defining the apertures 101B and 101C; the solid portion 101L overlies and spans a portion of the narrowing trench 105C, defining the apertures 101C and 101D; and the solid portion 101M overlies and spans a portion of the narrowing trench 105D, defining the apertures 101D and 101E. Figure 6A also illustrates the dashed line segment TT' shown in Figure 4.

Figure 6B illustrates flow paths along the manifold layer 101 of Figure 6A for the heat exchanger 300 shown in Figure 4. To simplify the present discussion, only the two flow paths 120 and 121 from Figure 1B are described in Figure 6B. As illustrated in Figure 6B, a cooling material is introduced into the inlet ports 197A-B by, for example, a pump (not shown). The cooling material then flows into the first reservoir 195 and then into the hollow finger 196B. Referring now to Figures 1B and 6B, the cooling material travels along the hollow finger 196B and down into the aperture 101B along the flow path 120. The "⊗" marking the flow path 120 in

Figure 6B indicates that the cooling material travels into the plane of the drawing and thus into the aperture 101B. The cooling material next travels within the channel defined by the narrowing trench 105A along the flow path 121 and out the aperture 101A. The "⊙" marking the flow path 121 in Figure 6B indicates that the cooling material travels out of the plane of the drawing and thus into the aperture 101A and into the hollow finger 190C. It will be appreciated that phrases such as "into" and "out of" used herein are used to help describe the direction of flow in reference to the drawings and are not intended to limit the scope of the present invention. Next, the cooling material traveling along the hollow finger 190C flows to the reservoir 198 and to the outlet ports 199A-B. From here, the cooling material can be removed from the heat exchanger 300 or cooled and reintroduced to the inlet ports 197A-B.

It will be appreciated that the cooling material introduced to the inlet ports 197A-B can and generally does travel along hollow fingers in addition to the hollow fingers 196B and 190C. The present discussion is limited to cooling material traveling along the hollow fingers 196B and 190C only to simplify the present description. Along the hollow finger 196B, the cooling material can and generally is introduced into apertures other than the aperture 101B. Along the aperture 101B, the cooling material can and generally does travel along paths other than the flow path 121, as illustrated in Figure 6B. For example, the cooling material traveling along the flow path 120 can be divided with a portion traveling along the flow path 122, as illustrated in Figure 1B. As described in more detail below, the heat exchanger 300 can also comprise an intermediate layer that determines which apertures the cooling material is introduced into, thus controlling the flow of cooling material above a heat-generating source.

Figure 7 illustrates a section of the heat exchanger 300 of Figure 4, with the top surface 189 removed. Figure 7 shows that section of the heat exchanger 300 of Figure 4 delimited by the plane RR'SS' and containing the first reservoir 195. The plane RR'SS' intersects the hollow fingers 190, the hollow fingers 196, the solid portions 101J-M, and the narrowing trenches 105A-D, all shown in Figure 4. Figure 7 is used to describe a three-dimensional flow path for a portion of a cooling material 103.

As illustrated in Figure 7, the cooling material 103 is introduced into the inlet port 197A, into the reservoir 195, along the hollow finger 196A, down to the aperture 101D, along the flow path 132 through the narrowing trench 105D, up to the aperture 101E, and up through the hollow finger 190A. The cooling material then flows in a direction out of and perpendicular to the page. Referring to Figure 4, the cooling material then flows into the second reservoir 198 and out one or both of the outlet ports 199A and 199B. Again referring to Figure 7, while traveling along the flow path 132, the cooling material absorbs heat generated by the heat-generating source 180 and conducted by that portion of the interface layer 105 substantially adjacent to the narrowing trench 105D. The cooling material carries the absorbed heat away from the heat-generating source 180, thus cooling the heat-generating source 180 at a location adjacent to the narrowing trench 105D. The cooling material circulating in the other narrowing trenches 105A-C cools the heat-generating source 180 in a similar manner at locations adjacent to the narrowing trenches 105A-C.

It will be appreciated that heat exchangers in accordance with the present invention can have many alternative configurations. For example, Figure 8 illustrates a heat exchanger 500 comprising the manifold layer 101 and interface layer 105, both of Figure 4, with an intermediate layer 310 positioned between the manifold layer 101 and the interface layer 105. As in Figure 4, Figure 8 shows the manifold layer with a portion of the top surface 189 cut away. The intermediate layer 310 can be used, for example, to allow cooling material to flow only into those channels that are above hot spots and to prevent cooling material from flowing into those channels that are not above hot spots. Thus, less cooling material is required and less energy is required for a pump circulating the cooling material.

As illustrated in Figure 8, the intermediate layer 310 has a plurality of apertures 311A-E, used to control the flow of the cooling material from the manifold layer 101 to the interface layer 105. While Figure 9 depicts one row of apertures 311A-E, it will be appreciated that the intermediate layer 310 can and generally does contain more than one row of apertures. Figure 9 depicts one row of apertures to simplify the present discussion. The use of the intermediate layer

310 in accordance with the present invention is described in relation to Figure 9.

Figure 9 is a side cross-sectional view of a section of the manifold layer 101, the intermediate layer 310, and the interface layer 105 of Figure 8. As illustrated in Figure 9, the aperture 311A is positioned between the hollow finger 190C and the narrowing trench 105A; the aperture 311B is positioned between the hollow finger 196B and the narrowing trenches 105A and 105B; the aperture 311C is positioned between the hollow finger 190B and the narrowing trenches 105B and 105C; the aperture 311D is positioned between the hollow finger 196A and the narrowing trenches 105C and 105D; and the aperture 311E is positioned between the hollow finger 190A and the narrowing trench 105D. In this way, the cooling material traveling along the flow path 317B is introduced into the hollow finger 196B and along the flow paths 316A and 316B. The cooling material traveling along the flow path 316A travels through the aperture 311A and into the hollow finger 190C. The cooling material traveling along the flow path 316B travels through the aperture 311C and into the hollow finger 190B.

Similarly, the cooling material traveling along the flow path 317D is introduced into the hollow finger 196A and along the flow paths 316C and 316D. The cooling material traveling along the flow path 316C travels through the aperture 311C and into the hollow finger 190B. The cooling material traveling along the flow path 316D travels through the aperture 311E and into the hollow finger 190A. Thus, as described below, by opening or closing the apertures 311A-C, the flow of cooling material through the heat exchanger 500 can be controlled.

Figure 10 shows a heat exchanger 600 having the manifold layer 101, the interface layer 105, both of Figure 8, and an intermediate layer 314 positioned between the manifold layer 101 and the interface layer 105. The intermediate layer 314 is configured to allow cooling material to flow only along the flow path 316D (Figure 11). As in Figures 4 and 8, Figure 10 shows the manifold layer 101 with a portion of the top surface 189 cut away. The intermediate layer 314 has the apertures 311D and 311E, but not the apertures 311A-C as shown in Figure 8. Thus, as illustrated in Figure 11, the cooling material is controlled to flow only along the flow path 316D and not along the flow paths 316A-C. Intermediate layers such as the intermediate layer 314 are

useful, for example, when a heat-generating source (not shown) coupled to a bottom surface of the interface layer 105 has non-uniform heat-generating portions. In one example, the heat-generating source needs to be cooled only below the narrowing trench 105D and thus below the flow path 316D. Intermediate layers such as that described here are taught, for example, in U.S. patent application Serial Number 10/439,635, Attorney Docket No. COOL-00301, filed on May 16, 2003, and titled "Method and apparatus for Flexible Fluid Delivery for Cooling Desired Hot Spots in a Heat Producing Device," incorporated by reference above.

Figures 12A-C are used to show features of a portion of a heat exchanger 790 in accordance with one embodiment of the present invention. Figures 12A-C show, respectively, a top view of an interface layer 705, a side cross-sectional view of a heat exchanger 790 formed from the interface layer 705 and a manifold layer 701, and a more detailed top view of the interface layer 705.

Figure 12A illustrates that the interface layer 705 has top surface 707 and narrowing trenches 705A and 705B. As illustrated in Figure 12A, the narrowing trench 705A has a first vertical edge wall 711 delineated by the line AA' and a second vertical edge wall 712 delineated by the line BB'. The line MM' bisects the interface layer 705 and is used below to describe features of the interface layer 705. As described in more detail below, in the discussion of Figure 12C, the narrowing trench 705A comprises two sloping sidewall sections 709 and 710 , each of which comprises two sloping sidewalls (709A and 709B, and 710A and 710B, respectively).

Figure 12B is a cross-sectional view of the heat exchanger 790, in accordance with one embodiment of the present invention. Figure 12B illustrates a cross section of the interface layer 705 of Figure 12A, taken along the line MM', and a cross-section of the manifold layer 701. The manifold layer 701 comprises an aperture 701A with a width W1 and an aperture 701B with a width W2. The narrowing trench 705A has a height H measured from a point X on the top surface 707 of the narrowing trench 705A to a point Y on a flat bottom surface 706 of the narrowing trench 705A. In the cross section shown, the narrowing trench 705A has a first sloping sidewall section 709 that extends from the point X to the point Y. Similarly, the

narrowing trench 705A has a second sloping sidewall section 710 that extends from a point X' on the top surface 707 of the narrowing trench 705A to a point Y' on the bottom surface 706.

Figure 12B further illustrates that the sloping sidewall section 709 (and thus, as described below, each of the sidewalls 709A and 709B that form the sidewall section 709) makes an angle $\theta 1$ with the bottom surface 706, measured clockwise from the bottom surface 706. The sidewall section 710 makes an angle $\theta 2$ with the bottom surface 706, measured counterclockwise from the bottom surface 706. Preferably, both $\theta 1$ and $\theta 2$ are between 0 degrees and 90 degrees. Also, preferably, $\theta 1$ equals $\theta 2$.

Referring now to Figure 12C, the sloping sidewall section 709 (Figure 12B) is comprised of two sloping sidewalls 709A and 709B angled to each other. Each of the sloping sidewalls 709A and 709B makes the angle $\theta 1$ with the bottom surface 706, measured clockwise from the bottom surface 706. The sloping sidewall section 710 (Figure 12B) is comprised of two sloping sidewalls 710A and 710B angled to each other. Each of the sidewalls 710A and 710B makes the angle $\theta 2$ with the bottom surface 706, measured counterclockwise from the bottom surface 706. As illustrated in Figure 12C, the line MM' bisects the heat exchanger 790, intersecting the sloping sidewall section 709 where the sloping sidewall 709A meets the sidewall 709B and where the sloping sidewall 710A meets the sloping sidewall 710B.

Still referring to Figure 12C, the narrowing trench 705A has a width G, the distance between the lines AA' and BB'. A length of the bottom surface 706 along the cross section MM', delimited by the line segment DD', has a length E. A width of an upper portion of the narrowing trench 705A along the line MM', delimited by the line segment CC', has a length V.

In a preferred embodiment, the height H is approximately 1mm, the widths W1 and W2 are both approximately 200 μm, the width G is approximately 20 μm, the length E is approximately 2 mm, and the length V is approximately 3.4 mm. It will be appreciated that in accordance with the present invention, H can be larger or smaller than 1mm, one or both of W1 and W2 can be larger or smaller than 200 μm, G can be larger or smaller than 20 μm, and E can be larger or smaller than 2 mm. It will also be appreciated that the dimensions of the trench

705B can differ from those of the trench 705A; the dimensions of both are depicted as similar merely for ease of illustration. Preferably, H is chosen large enough to provide structure for the heat exchanger 790 and to withstand the heat generated by a heat-generating source coupled to the heat exchanger 790. Preferably, H is also small enough to allow heat to radiate quickly and efficiently to a cooling material circulating in the channels of the heat exchanger 790. In one embodiment, the above values are chosen to provide aspect ratios for the narrowing trenches of 10:1 or larger. It will be appreciated, however, that the dimensions can also be chosen to provide depth:width aspect ratios smaller than 10:1.

Figures 13A-D depict steps used to fabricate a narrowing trench (and thus a channel) and a portion of a manifold layer, in accordance with one embodiment of the present invention. While Figures 13A-D depict the formation of one narrowing trench, it will be appreciated that by using appropriate masks, the steps illustrated in Figures 13A-D can be used to form a plurality of narrowing trenches in accordance with the present invention.

Figure 13A illustrates a material 805 having a <110> orientation with a mask 815 formed or deposited over a surface of the material 805. The mask 815 is patterned using, for example, photo-lithographic processes to expose areas that will later define the narrowing trenches. The material 805 exhibits anisotropic etching, as described below. Preferably, the material 805 is <110> oriented silicon. It will be appreciated that etching <110> oriented silicon will expose <111> oriented sidewalls of the silicon. Alternatively, the material 805 is any orientation of silicon or any other material or composite of materials that together exhibit anisotropic etching.

The material 805 is then exposed to an etchant, such as a wet etchant, to expose the <111> oriented planes (i.e., the sidewalls 811 and 812) and a bottom surface 813, as illustrated in Figure 13B, of the resulting narrowing trench 805A. Alternatively, the material 805 is etched in an anisotropic plasma etch. As illustrated in Figure 13B, the sloping sidewall 811 makes an angle $\theta 3$, measured clockwise from the a bottom surface of the trench 805A, of approximately 54.7 degrees. It will be appreciated that the present invention contemplates sidewalls having other angles with the bottom surface of the trench 805A, angles preferably greater than 0 degrees

but less than 90 degrees. The present invention also contemplates forming angled sidewalls within this range by, for example, combining piecewise sections to form an angled sidewall.

Preferably, the mask 815 is formed of a material substantially resistant to the etchant. Etchants used in accordance with the present invention include, but are not limited to, potassium hydroxide (KOH) and tetramethyl ammonium hydroxide (TMAH). Masks used in accordance with the present invention can comprise nitrides, oxides such as SiO_2, and some metals.

Next, as illustrated in Figure 13C, the mask 815 is removed, using any of a variety of techniques. Next, as illustrated in Figure 13D, a manifold layer 810 is coupled to the interface layer 805. The manifold layer 810 can be coupled to the interface layer using a variety of techniques, including adhesive bonding, thermal fusing, anodic bonding, eutectic bonding, or other any other form of bonding. Alternatively, the manifold layer 810 and the interface layer 805 can be formed from a single monolithic device during device fabrication. Preferably, the manifold layer 810 is formed and oriented so that the resulting apertures all lie substantially in a single plane, substantially parallel to the bottom surfaces of the narrowing trenches. The manifold layer 810 can be formed from a variety of materials including, but not limited to, a plastic, a glass, a metal, a semiconductor, and a composite of materials.

Next, the interface layer 805 can be coupled to a heat-generating source, such as a semiconductor device. Alternatively, the heat-generating source can be integrally formed with a bottom surface of the interface layer 805, for example in one or more semiconductor device fabrication steps. A pump (not shown) can then be coupled to the manifold layer 810, as described above, to pump the cooling material through the heat exchanger and thus cool the heat-generating source. The cooling material can comprise a liquid, such as water, a gas, air, a vapor, or a combination of these.

Alternatively, the interface layer 805 can be manufactured from a metal, such as copper, using standard machining processes to form the narrowing trenches. These machining processes can include, but are not limited to, milling, sawing, drilling, stamping, EDM, wire EDM, coining, die casting, investment casting, or any combination of these. Alternatively, the interface layer

805 can be formed by other processes, including, but not limited to, electroplating, metal injection molding, LIGA processes, casting, or any combination of these.

Heat exchangers in accordance with the present invention provide smooth flow paths (channels) in which cooling materials travel. Such structures work more efficiently and thus reduce the load on the pumps pumping the cooling material through the heat exchanger. The method of manufacturing heat exchangers in accordance with one embodiment of the present invention are relatively inexpensive. Materials exhibiting anisotropic etching are chemically etched, preferably using wet chemistries, to form narrowing trenches that ultimately form the flow paths. The use of wet chemistries is inexpensive and quick compared to other device fabrication processes. The present invention can thus be used to inexpensively fabricate heat exchangers used to cool a variety of devices, such as semiconductor devices, motors, batteries, walls of process chambers, or any device that generates heat.

The present invention has been described in terms of specific embodiments incorporating details to facilitate the understanding of the principles of construction and operation of the invention. As such, references herein to specific embodiments and details thereof are not intended to limit the scope of the claims appended hereto. It will be apparent to those skilled in the art that modifications can be made to the embodiments chosen for illustration without departing from the spirit and scope of the invention.